PB86-176377

Perspective on Performance Variability in Municipal Wastewater Treatment Facilities

(U.S.) Environmental Protection Agency
Cincinnati, OH

Apr 86

U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-176377

EPA/600/D-86/064
April 1986

A PERSPECTIVE ON PERFORMANCE VARIABILITY IN MUNICIPAL WASTEWATER TREATMENT FACILITIES

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U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/D-86/064		

4. TITLE AND SUBTITLE	5. REPORT DATE
A Perspective on Performance Variability in Municipal Wastewater Treatment Facilities	April 1986
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Lewis A. Rossman and John J. Convery	
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Environmental Protection Agency Water Engineering Research Laboratory 26 W. St. Clair Street Cincinnati, Ohio 45268	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Water Engineering Research Laboratory - Cinti. Ohio Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES
Project Officer: Lewis A. Rossman (513/569-7603)

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	11
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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A Perspective on Performance Variability in Municipal Wastewater Treatment Facilities

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Excessive variability in effluent quality can cause wastewater treatment plants to fail to meet their discharge permit limits. This paper summarizes our understanding of the nature, causes, and control of this variability. It discusses studies made on the differences in performance variability observed among plants, the statistical characterization of this variability, and investigations into its causes. Methods of controlling and accomodating effluent variability are briefly reviewed. The results of an EPA workshop to develop research objectives related to these problems are discussed.

Introduction

Estimates indicate that a significant number of the Nation's 21,000 municipal wastewater treatment facilities do not consistently meet their discharge permit limits (U.S.Government Accounting Office, 1983; Water Pollution Control Federation, 1985). Surveys show that aside from gross design errors and chronic mismanagement, most noncompliance can be related to a lack of process control capability resulting in excessive variability of effluent quality (Gray, et al., 1982; Government Accounting Office, 1983). In addition to permit noncompliance, this variability can cause excessive periods of adverse impacts in receiving waters.

The purpose of this paper is to provide a perspective on our understanding of the characterization and causes of effluent variability, and on our ability to either control it operationally or to accomodate it through facility design. The paper also reports on the results of a structured group process used by US EPA's Water Engineering Research Laboratory to prioritize future research objectives in this area.

Characterization of Effluent Variability

Investigators have characterized wastewater treatment plant effluent variability in a number of different ways. The simplest and most common measures have been the standard deviation of effluent concentration measurements and its related statistic, the coefficient of variation (CV). The latter quantity is the standard deviation divided by the mean and offers a scale-free measure of variability. The time scale used to analyze effluent variability has ranged from

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hourly measurements to monthly averages, depending on the purpose of the analysis. The most commonly used time frame is based on daily average values. Other measures of variability have included effluent concentration percentiles (the concentration not exceeded more than a given percent of the time) and the frequency and duration of "upsets" (periods where effluent quality is significantly worse than some reference level).

Levels of variability differ significantly among treatment facilities. Effluent CV's typically span a range of 0.2 to 1.2. Figure 1 displays the variation in the means and CV's of daily effluent BOD (Biochemical Oxygen Demand) from 37 well-operated activated sludge plants (Niku, et al., 1979). Figure 2 plots the medians of the mean and CV of daily effluent BOD from plants in eight process categories based on a survey of 324 plants (U.S. EPA, 1984b). The individual plants contained in any given category show considerable scatter about the median point plotted in Figure 2. There appears be a trend towards higher levels of relative variability for process categories that achieve lower mean levels of effluent BOD.

Numerous studies have been made that statistically characterize the performance variability of individual plants. Histograms showing the frequency with which effluent concentrations fall within specific intervals are typically skewed to the right, showing that "low" values are more probable than "high" ones (Berthouex, 1974; Niku, et al., 1979). Figure 4 shows such a histogram for the daily series of effluent BOD values observed from an activated sludge plant in Michigan as plotted in Figure 3. Various types of standard probability distribution functions have been fitted to such data. No single distribution type has been found suitable for all plants. The lognormal distribution is the one that provides an adequate fit most often (Hann, et al., 1972; Dean and Forsythe, 1976; Niku, et al., 1979). Figure 5 presents a lognormal probability plot for the data of Figure 3. The straight line shape of this plot indicates that the data do fit a lognormal distribution.

Strictly speaking, the use of probability plots and goodness of fit tests for standard probability distributions is only valid for data which are statistically independent and random. The sequence of effluent quality levels found in continuous plant records are not completely random. They can display considerable amounts of deterministic periodicities and autocorrelation (Thomann, 1970; Hann, et al., 1972; Adams and Gemmell, 1973). Fourier Analysis (Bendat and Piersol, 1966) can be used to represent systematic cyclic variations as a weighted sum of sine and cosine terms of different time frequencies. For example, 31% of the variation in the BOD levels of Figure 3 could be explained by weekly, monthly, bi-monthly, semi-annual and annual periodicities.

The lag k autocorrelation coefficient of a time series measures the degree of dependence of an observed value with one measured k time units before it. The coefficient can vary from -1 to +1. Positive correlation implies that when one value is high (or low) relative to the mean, the other is also high (or low). Independent meas-

Figure 1. Mean and Coefficient of Variation of Effluent BOD From 37 Activated Sludge Plants

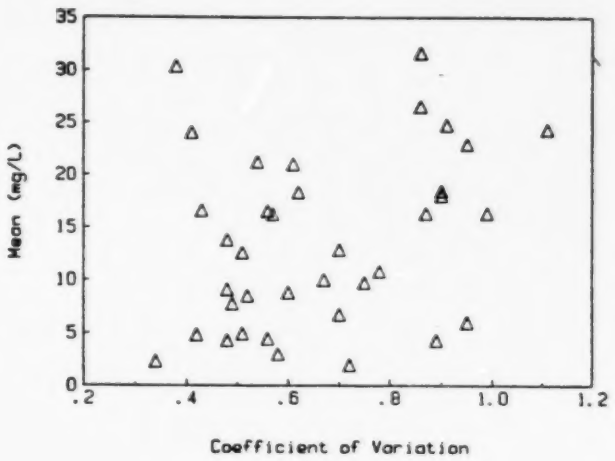


Figure 2. Mean and Coefficient of Variation of Effluent BOD for the Median Plant From a Survey of 324 Facilities

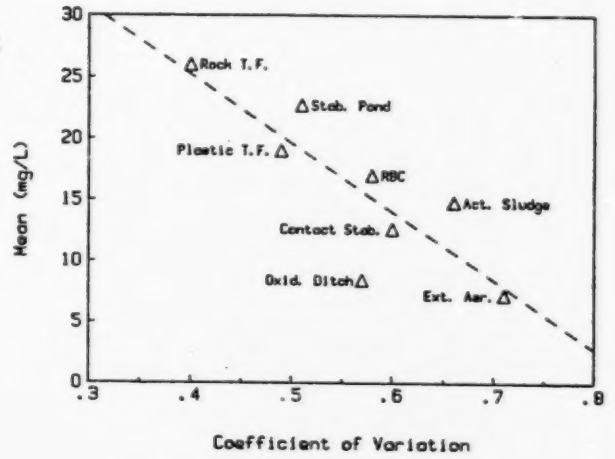


Figure 3. Time Series of Daily Effluent BOD From an Activated Sludge Plant in Michigan

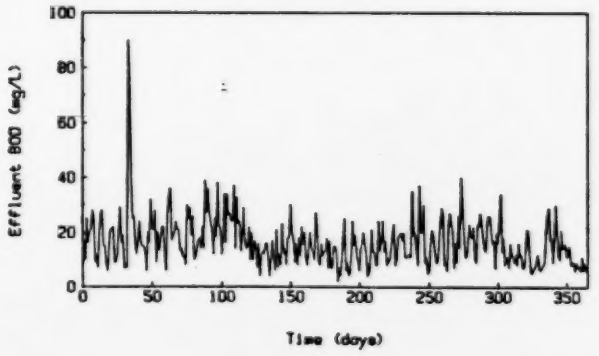


Figure 4. Histogram of Effluent BOD Levels For Data of Figure 3

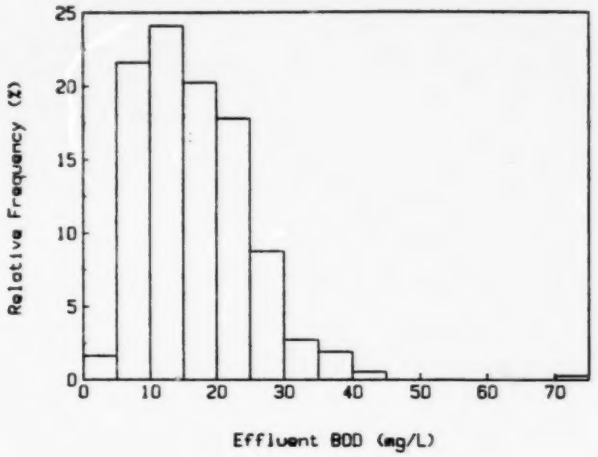


Figure 5. Lognormal Probability Plot of the Effluent BOD Data of Figure 3

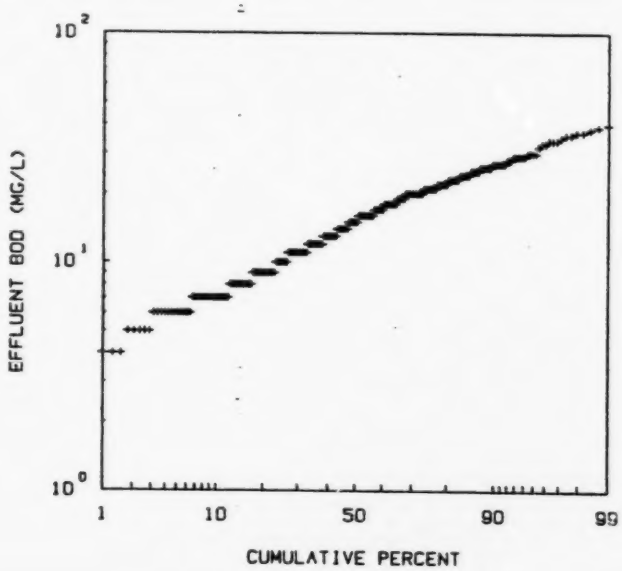
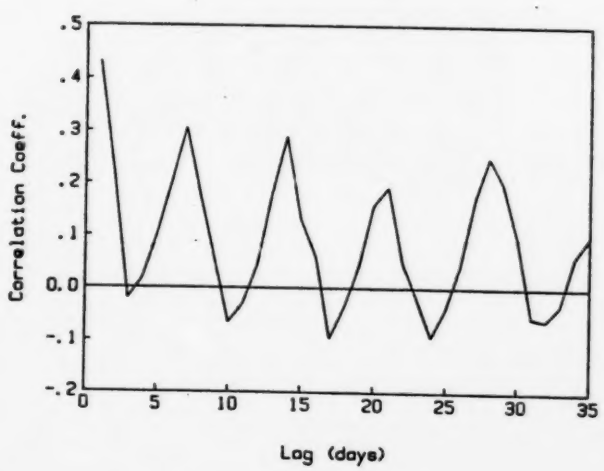


Figure 6. Correlogram of the Effluent BOD Data of Figure 3



urements have zero autocorrelation. First order (lag 1) autocorrelations for effluent BOD from activated sludge plants have been found to range between 0.3 and 0.55 (Adams and Gemmell, 1973). For trickling filters, coefficients between 0.36 and 0.85 have been reported (US EPA, 1984b). Figure 6 displays the correlogram (a plot of autocorrelation versus lag) of the data in Figure 3. The influence of a weekly periodicity is clearly evident from this plot.

Factors Affecting Effluent Variability

A number of investigators have attempted to establish statistically valid relationships between effluent variability and variations in such causative factors as influent pollutant loading, water temperature, and process operating conditions. The most ambitious effort of this kind found no consistent set of relations (Niku and Schroeder, 1981). In applying regression analysis to 21 different activated sludge plants, only 13-61% of the effluent BOD variability and 5-52% of the SS (suspended solids) variability could be explained by sets of such factors. For BOD, the factors appearing most frequently in the 21 regressions were temperature (6 times), time (4), and influent loading (4). For SS they were flow (6) and sludge volume index (5).

Similar results were obtained using more sophisticated time series transfer function modeling techniques at two other activated sludge plants (Bertheoux, et al., 1976; Debelak and Sims, 1981). These analyses showed that most of the variability in effluent BOD (or COD) could be explained by past values. Inclusion of causative factors in the models provided only a slight improvement in their explanatory power.

A systematic analysis of the factors causing "upset" conditions at 15 activated sludge plants has also been made (Bertheoux, et al., 1985). Upsets were subjectively identified as periods where performance was not typical of the recent past. Of 24,554 days of operation analyzed, 8.8% and 8.1% were characterized as BOD and SS upsets, respectively. Causes of the upset periods were determined by examining operating records and interviewing plant operators. The two most frequently assigned categories of causes were "operational problems" and "influent variables". Together they accounted for 61% of the BOD upsets and 60% of the SS upsets. A more specific listing of the most frequently observed causes is as follows:

Factor	Percentage of Upset Days Attributed to Factor	
	BOD	SS
High Flows	11	19
Solids Handling Problems	13	17
Low Mixed Liquor SS	13	9
Low Dissolved Oxygen	19	10

Mechanical failures accounted for only about 1% of the upset days. This confirms the mechanical component reliability data collected from 9 other plants (Shulz and Parr, 1982) indicating high availabilities for most components (e.g., > 98%). Availability is the percent of the time that a component is operational. Some exceptions to this finding were gas engines (93% availability), vacuum filters (93%), ball valves (87%), and incinerators (72%). The effect of mechanical component outages at these plants on effluent quality was not addressed.

The studies cited above suggest that on a day-to-day basis, the activated sludge process is relatively insensitive to variations in process parameters that remain within "acceptable" bounds. Only when these bounds are exceeded is the cause and effect relation readily identifiable. Under normal operation, the variations in process performance may be attributable to inherent process "noise" or to the effects of unobservable phenomena (e.g., parameter disturbances with durations shorter than the time scale used to measure effluent variability).

Approaches to Controlling Effluent Variability

Aside from the problems related to overloading, faulty design, and inadequately trained operators, a number of approaches can be suggested for either controlling or accomodating the effects of effluent variability. A brief sampling of these approaches is as follows:

Design redundancy and excess capacity (Niku, et al., 1979; US EPA, 1984a): accomodates effluent variability through a reduction in the design mean effluent concentration level.

Control charts and reference distributions (Fairall, 1973; Berthouex and Hunter, 1983): helps the operator know when a plant is "out of control" and special diagnoses or operational changes are called for.

Computer-assisted control (Stephenson, et al., 1983; Johnson, et al., 1984; Keck, et al., 1985): helps maintain dissolved oxygen, solids retention time, and clarifier solids loading within acceptable limits to avoid upset conditions.

Reliability evaluations (Waste & Water International, 1982): provides a comprehensive engineering study of all aspects of a plant's performance reliability and recommends remedial actions if needed.

No systematic study has been performed to assess the relative effectiveness or cost-efficiency of these various approaches. None of these methods allows a priori predictions to be made of the level of variability reduction that they can achieve.

Research Needs

The US EPA Water Engineering Research Laboratory held a workshop in December 1984 to identify and prioritize research objectives in

the area of municipal wastewater treatment plant performance reliability (Christakis and Keever, 1984). The highest ranking objectives formulated at this workshop were as follows:

- Develop improved plant operational aids such as:
  computer-based expert systems,
  tools to help diagnose departures from normal performance,
  statistically valid control charts.

- Improve the ability of hybrid mechanistic-stochastic models to predict plant performance variability.

- Determine guidelines for designing plants to achieve specific levels of effluent variability.

- Determine how to incorporate uncertainty about plant performance prior to construction into the water quality planning and permit setting process.

The Water Engineering Research Laboratory is currently pursuing research projects directed at the first of these objectives, the development of improved plant operational aids.

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